Modeling the Evolution of Climate Change Assessment Research Using Dynamic Topic Models and Cross-Domain Divergence Maps

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Abstract

Climate change is an important social issue and the subject of much research, both to understand the history of the Earth's changing climate and to foresee what changes to expect in the future. Approximately every five years starting in 1990 the Intergovernmental Panel on Climate Change (IPCC) publishes a set of reports that cover the current state of climate change research, how this research will impact the world, risks, and approaches to mitigate the effects of climate change. Each report supports its findings with hundreds of thousands of citations to scientific journals and reviews by governmental policy makers. Analyzing trends in the cited documents over the past 30 years provides insights into both an evolving scientific field and the climate change phenomenon itself. Presented in this paper are results of dynamic topic modeling to model the evolution of these climate change reports and their supporting research citations over a 30 year time period. Using this technique shows how the research influences the assessment reports and how trends based on these influences can affect future assessment reports. This is done by calculating cross-domain divergences between the citation domain and the assessment report domain and by clustering documents between domains. This approach could be applied to other social problems with similar structure such as disaster recovery.

Introduction

Given a particular field of scientific study which has a measurable impact on society, or that pertains to extreme events that affect the world on a global level, committees or panels are often formed to compose reports and recommendations to governments or global enterprises. Often these reports may be based upon the collective work of many individual experts, and on large bodies of scientific literature and observational data. Such reports are often updated periodically.

The sheer volume of information involved makes it difficult for policy makers, general public and even scientist to assimilate the research and comprehend the evolving findings and recommendations. Concepts of interest that have potential research momentum may be overlooked. Understanding these slow growing concepts requires insight into the evolution of the research. The analysis performed could give early indication of a new area of research that might be overlooked. Statistically, this work could also shed light on concepts that are declining and concepts that are splitting into sub-areas.

This early work includes a method that can integrate multiple temporal domains in order to perform automatic summarization and correlation to support human analysis. Dynamic topic modeling is used to model different domains temporally, these domains are then combined based on the models and using Jensen-Shannon divergences, in order to perform temporal cross-domain analysis. Documents cluster within a domain and across domains to show inter-domain and cross-domain temporal influence. Within a domain and across domains, this method discovers which documents are related or are similar. Understanding the influence between large document domains over time is harder, if not impossible, to achieve by a person.

Use Case

The Intergovernmental Panel of Climate Change (IPCC) Assessment Reports is a panel which periodically publishes assessments for climate change (IPCC b). There have been five IPCC Assessment Reports to date, approximately every five years dating back to 1989, the latest leading to a Paris Agreement in December 2016 (Nations 2015), signed thus far by 172 nations to limit the amount of global greenhouse gases emitted to producing no more than a 2° C warming of the atmosphere. These reports are a living evolving big data collection tracing 30 years of climate science research, observations, and model scenario inter-comparisons. They contain more than 200,000 citations over a 30 year period that trace the evolution of the physical basis of climate science, the observed and predicted impact, risk and vulnerability to climate change and its mitigation and adaptation approaches for policy on greenhouse gases and impact on climate change (IPCC a).

It is not feasible for a climate scientist to know all of the literature in all of the disciplines related to the physical science and how the science will lead to various regional and global potential impacts, no less the mitigation responses. Having a tool which automatically processes past assessments and citation information could reduce the time spent in composing future assessment reports. A search of past models and previously published research can save the researcher hours of time as opposed to manually inspecting and reading each document. Moreover, this approach automatically links authors of research across assessment reports and citations, providing the researcher with ways to see social networks among climate change researchers. However most importantly, this method can show which chapters across assessment reports spanning 30 years are directly related and which chapters are directly related to both current and previous research papers. This provides a powerful way to understand 30+ years of research.

Background

The structure of the IPCC Assessment Reports (AR) and a brief background of dynamic topic modeling are given. In this work, the following IPCC assessment reports were used for experimentation and analysis: AR 1 (Houghton, Jenkins, and Ephraums 1990; Tegart, Sheldon, and Griffiths 1990; Bernthal et al. 1990), AR 2 (Houghton et al. 1995; Watson et al. 1995; Bruce et al. 1995), AR 3 (Houghton et al. 2001; McCarthy, Canziani, and others 2001; Davidson, Metz, and others 2001; Watson and the Core Writing Team 2001), AR 4 (Solomon et al. 2007; Parry et al. 2007; Metz et al. 2007; Pachauri, Reisinger, and others 2007), and AR 5 (Stocker et al. 2013; Barros et al. 2014; Edenhofer et al. 2014; Pachauri et al. 2014).

IPCC Assessment Report Structure

The IPCC Assessment Reports comply with a formal structure and is mostly composed of four distinct books (i.e. Physical Science Basis, Impacts, Adaptations and Vulnerability, Mitigation of Climate Change and Synthesis Reports). AR 1 and AR 2 consist of three books and they roughly align with the other assessment periods. Each book has roughly 11 or more chapters and each chapter contains about 800 to 1200 citations.

This structure is formally defined as follows:

There are n reports $ar_1, ar_2, ..., ar_n$, currently $n = 5$.

There are m books $br_{n,1}, br_{n,2}, ...br_{n,m}$ where $br_{n,m} \subset ar_n$, currently $m = 4$ for all ar_n.

There are $l(m,n)$ chapters $ch_{n,m,1}, ch_{n,m,2}, ...ch_{n,m,l}$ where $ch_{n,m,l} \subset br_{n,m}$.

For each $ch_{n,m,l}$, $k(m,n,l)$ citations $ci_{n,m,l,1}, ...ci_{n,m,l,k}$ found in that document are extracted. The citations are stored in a directory structure by chapter, by year.

Topic Modeling

Dynamic Topic Modeling (DTM) (Blei and Lafferty 2006) is a form of topic modeling that models discrete topics over time. Foundational to DTM is Latent Dirichlet Allocation (LDA) (Blei, Ng, and Jordan 2003; Blei 2012), a generative topic modeling approach that uses a Dirichlet prior and Bayesian estimation. Every document is assumed to be a mixture of topics represented as a probability distribution, and each topic is a probability distribution over the terms in the vocabulary that is formed from the full collection of documents. Topics are drawn from a Dirichlet distribution. Known as a generative model, the joint probability distribution is obtained over observed and hidden variables (Blei, Ng, and Jordan 2003; Blei 2012). Computing the posterior is achieved by estimation, either using a variational method such as an EM algorithm (McLachlan and Krishnan 2007) or a sampling method such as Gibbs sampling (Griffiths 2002).

The goal of DTM is to capture how topics are changing over discrete time periods. Documents are split into time slices and a topic model is composed for each time slice then linked together where topics and topic proportions are allowed to 'evolve' over the set of time slices. A normal distribution is used over topics and approximate inference is achieved using an EM algorithm (McLachlan and Krishnan 2007). A more in-depth description of this work is described by (Blei and Lafferty 2006).

Related Work

Recent developments in topic modeling have started exploring its applicability to scientific concepts. Hall et al. (Hall, Jurafsky, and Manning 2008), address how scientific ideas have changed over time by modeling temporal changes employing DTM, with probability distributions for the ACL Anthology, a public repository of all papers in the Computational Linguistics journals, conferences and workshops. Their work proposes extensions to their model by integrating topic modeling with the citations as done in this paper. Tang et al. (Tang and Monteleoni 2015) investigate the use of topic modeling to identify extreme events based on numerical atmospheric model simulations. They associate text terms with statistical ranges of numerical variables. Li et al. (Li, Jin, and Long 2012), have developed a topic correlation and J-S Divergence measure for cross-domain text classification by treating three separate term vocabularies. Wang et al. (Wang, Blei, and Heckerman 2012), extends DTM by assuming that time is continuous, increasing temporal resolution. Shalit et al. (Shalit, Weinshall, and Chechik 2013) use DTM to establish musical influence of songs based on a continuous data set ranging from 1922 to 2010. They structure their problem similarly to work described in this paper, in that they represent data in terms of a hierarchical structure: sound segments - songs - album structure. Other work that used a dynamic topic modeling approach that were less relevant to this work includes work by Hu et al. (Hu et al. 2015) and Wang et al.(Wang and McCallum 2006).

Methodology

The methodology includes pdf to text conversion of documents, citation retrieval, text pre-processing, model generation, model correlation, and cross-domain document clustering. Each of these steps is described in more detail.

PDF to Text Conversion and Citation Retrieval

The IPCC documents are in the form of PDF files. PDF files are converted to text using a Python-based converter [1]. As the conversion process can result in a significant amount of 'noisy' text, the noisy text is addressed in the preprocessing stage by using a custom aggressive noise eliminator.

[1] https://pypi.python.org/pypi/pdfminer/

As previously described, each report contains a set of chapters. Each chapter typically contains a set of citations. For example, in AR 1, the book which describes the *impact* of climate change contains a chapter 2 which has approximately 200 referenced citations (Tegart, Sheldon, and Griffiths 1990).

From each chapter, the set of referenced citations are extracted by parsing the raw text that was produced from the pdf to text conversion. Reports and books can be formatted differently. This creates a challenge for accurately parsing and retrieving a complete set of citations.

To understand how well the parser performed, chapters were randomly selected and the number of citations were manually counted. This count was compared to how many citations were obtained through parsing. On average, through the pdf to text conversion and text parsing, over 80% of the citation information from the chapters were obtained. For each parsed citation, the actual publication is retrieved using Microsoft Bing Search API (Bing).

Preprocessing

A word n-gram model is used that assigns higher weights to phrases that are defined in a custom-built climate change glossary. Lemmatization and stopword removal is performed and functional and numeric words are removed. Words with low frequency and words with a length less than three are also removed to reduce the noise incurred during the PDF to text conversion, as often mistakes in the conversion result in stray characters or incomplete words.

Model Generation

The codebase DTM (Blei and Lafferty) , written in the C programming language, is used to build dynamic topic models both of the assessment reports and of the citations referenced in the chapters. Experiments were performed that included constructing topic models by changing K, the number of topics, and by changing a parameter that affects the variance of the topic chains. Custom code written in Python is used to wrap the DTM code so as to process the probability distributions that are processed by the DTM code.

As with LDA, generating a model involves calculating the frequency of each word found in a document. In this work, models based on assessment reports are built, where a document d is defined to be a chapter. Models for citations are also constructed, where a document d is defined to be a single full text publication.

Five discrete time slices representing the five IPCC assessment periods are used in this work. Though citations could be modeled continuously, in this work they are constrained to the five discrete time slices. An example topic created using DTM given these 5 discrete time slices is shown in Table 1. In this example, the top 10 most probable terms for a topic given each time slice are shown. It could be observed that among assessment periods 1 and 2, there is no change in the top 10 terms. However, there is variation among assessment periods 3, 4 and 5.

Table 1: Dynamic Topic Generation IPCC Example Topic Mitigation.

Topic Example - Top 10 Terms		
Assessment Period 1	*Assessment Period 2*	
climate change	climate change	
radiative forcing	radiative forcing	
temperature	temperature	
kyoto protocol	kyoto protocol	
land use	land use	
adaptation	adaptation	
clean development mechanism	clean development mechanism	
greenhouse gas	greenhouse gas	
global warming	global warming	
climate model	climate model	
Assessment Period 3	*Assessment Period 4*	*Assessment Period 5*
climate change	climate change	adaptation
kyoto protocol	adaptation	climate change
clean development mechanism	temperature	global mean surface temperature
radiative forcing	radiative forcing	surface temperature
temperature	kyoto protocol	equilibrium climate sensitivity
land use	land use	carbon dioxide
adaptation	equilibrium climate sensitivity	temperature
global warming	surface temperature	land use
climate model	clean development mechanism	anthropogenic
greenhouse gas	climate model	radiative forcing

Cross-Domain Modeling and Correlation

Cross-domain modeling is used and the results are evaluated to answer the question, how can influence between two domains be measured? The two domains can be subdomains of a larger domain. For example, *Physical Science*, *Impact* and *Mitigation* are all subdomains of the larger domain *Climate Change*. Or the domains could be less related such as *Climate Change* and *Health Care*.

Cross-domain modeling describes a process of taking two dynamic topic models that represent different domains and combining these two models into one single representation. This representation can be used to overcome differences in vocabulary and identify which domain influences another domain by grouping documents from the two domains based on how similar topics are to each other across the two domains. These two domains are correlated without necessarily creating a third shared topic model as in previous work (Li, Jin, and Long 2012). Instead correlation is based on an additional filtering method which uses the two existing topic models.

In this work, cross-domain modeling is used and correlation is performed for subdomains with the IPCC Assessments. The *Physical Science* is the study of the physical, chemical and biological mechanisms and includes the observations and models, representing the theoretical work from the past, present and future (Houghton, Jenkins, and Ephraums 1990; Houghton et al. 1995; 2001; Solomon et al. 2007; Stocker et al. 2013). The *Impact* report assesses the impact on the ecosystems and socio-economic systems, especially anthropogenic influences (Tegart, Sheldon, and Griffiths 1990; Watson et al. 1995; McCarthy, Canziani, and others 2001; Parry et al. 2007; Barros et al. 2014). The *Mitigation* report relates to ways to mitigate climate change through strategies that include conservation, renewable energy, carbon capture and sequestration, and geoengineering (Bernthal et al. 1990; Bruce et al. 1995; Davidson, Metz, and others 2001; Metz et al. 2007; Edenhofer et al. 2014). For this reason, the *Physical Science* is modeled to determine how the research influences the *Impact* report and how it influences the *Mitigation* report. In addition, the *Impact* research is modeled to understand how it influences the *Mitigation* report. In addition, how research papers referenced by a particular report influences that report are also modeled, i.e *Physical Science* citations and the *Physical Science* report.

Dynamic topic models for each domain are generated, for example the first domain could be *Physical Science* citations and the second domain could be the *Impact* report. The term probability distributions and the Jensen-Shannon divergence method are used to find topic pairs across domains that have low divergences. Cross-domain low divergence topic pairs are used to discover documents from the citation domain that influence the report chapters.

A 'micro-filtering' technique is used based on high ranked terms and high ranked topics. Using the term probabilities for each topic, the n highest ranked terms are calculated. For each document, the m highest ranked topics are calculated using topic probabilities.

By using 'micro-filtering' new topic 'micro-models' are formulated. Given two topic domains d_1 and d_2, a new topic domain d_3 is created as a composition of d_1 and d_2. Given V_1 and V_2, the vocabulary V_s formed by 'micro-filtering' is defined as $V_s = V_1 \cup V_2$. Based on V_s and calculated probability distributions, divergences are measured using Jensen-Shannon divergence for each combination of topics across the two domains.

The Jensen-Shannon divergence between two probability distributions $P1$ and $P2$ is defined as:

$$JSD\,[P1, P2] = \frac{1}{2}(KL[P1, \frac{P1+P2}{2}] + KL[P2, \frac{P1+P2}{2}]) \tag{1}$$

Where KL is the Kullback Leibler divergence.

	Mitigation Reports Topic 1					Mitigation Reports Topic 2				
Physical Science Citations Topic 1	.53	.55	.58	.55	.57	.61	.68	.63	.64	.64
Physical Science Citations Topic 2	.38	.43	.51	.43	.41	.29	.12	.09	.14	.15
Physical Science Citations Topic 3	.38	.43	.51	.43	.41	.29	.12	.09	.14	.15

Figure 1: Divergence Between Domains Example.

As shown in Figure 1, the divergence is calculated between two domain topics, where each individual cell in this matrix has a divergence for each time slice. Divergences of .1 and below are used in this work. The smaller the threshold, the few pairs will be used to obtain documents across the two domains. Future experiments will explore the effects of increasing this threshold. An example of a cross domain divergence matrix is shown in Figure 2 which shows how these two domains intersect based on their topic divergences filtered by this threshold.

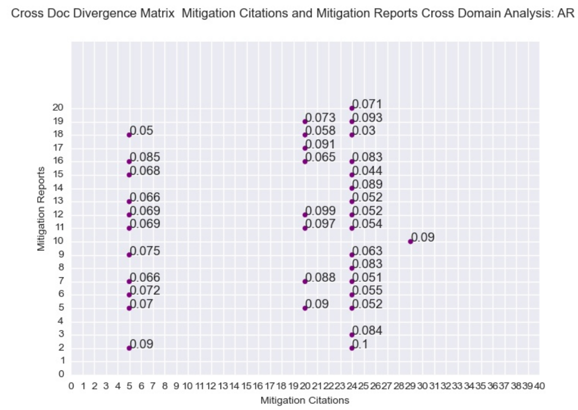

Figure 2: Cross Domain Divergence Matrix Example - Mitigation Report Topics and Mitigation Citation Topics Example.

Cross-Domain Clustering

Documents in each domain, based on the DTM, have an associated topic probability distribution. Ordered by their highest probability, an example of these document topic vectors is shown in Figure 3. Each document has a vector of topics with an associated probability. This vector forms a mixture of topics and proportionally defines the themes present in a given document.

	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
AR 1 – Chapter 6 Mitigation	Topic 12	Topic 15	Topic 4	Topic 3	Topic 5	Topic 8
AR 1 – Chapter 5 Mitigation	Topic 12	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5
AR 1 – Chapter 4 Mitigation	Topic 4	Topic 15	Topic 20	Topic 17	Topic 3	Topic 18

Figure 3: Document Topic Distributions Example.

Given a pair of correlated topics, the documents from each domain which have a probability for the specific topic above a designated threshold are used and are clustered together. This method not only provides a way to cluster citations from the citation domain and report chapters from the report domain but since all citations are associated with a chapter for which they were referenced, chapters from the two domains based on the clustered citations can also be used, along with specific author names and other interesting attributes.

Experiments and Results

Three experiments were performed as described in Tables 2 where in each experiment a dynamic topic model was built for a set of chapters from a particular book for each assessment period and for the set of citations found in each book for each assessment period.

Table 2: IPCC Cross-Domain Experiments Performed using Documents and Citations.

Experiment	*M1*	*M2*	*M1 Word Count*	*M2 Word Count*
1	Physical Science Citations	Impact Report	15500	4400
2	Physical Science Citations	Mitigation Report	15500	4000
3	Impact Citations	Mitigation Report	22200	4000

Report and citation statistics are described in Tables 3 and 4. There is clearly a large discrepancy in the number of documents used in the report model and the number of documents used in the citation model. For this reason, a lower K is used for the report model and a higher K for the citation model.

Table 3: Document Chapter Counts By Assessment.

Assessment Report	*Physical Science*	*Impact*	*Mitigation*
AR1	11	7	11
AR2	11	28	11
AR3	14	19	10
AR4	11	20	13
AR5	14	30	16

Table 4: Citation Counts By Assessment.

Assessment Report	*Physical Science*	*Impact*	*Mitigation*
AR1	1655	1994	182
AR2	5617	11339	3423
AR3	6942	7139	3368
AR4	15189	21698	8104
AR5	23564	34614	3509

For each experiment, micro-filtering was applied and cross-domain correlations were calculated using the Jensen-Shannon divergence. Documents were clustered based on low divergence topic pairs.

Experiments were conducted on a 1.80 GHz Xeon CPU with 64 GB of memory. It took approximately two days of continuous running to produce each of the citation models. Report models took no longer than two hours to complete.

Citation Retrieval

Over 150,000 citations were retrieved, extracted from the chapters of the assessment reports of the four books. To measure how many citations were actually successfully retrieved, precision, recall and F-Measure were calculated. It is important to note that research papers can be retrieved that were not necessarily referenced in the chapters. This is due to errors in the pdf to text conversion and also due to errors in the Bing search process. For example, certain publication are simply not obtainable using the Bing API. The results of this analysis are shown in Table 5.

Topic Mixtures

To evaluate how well the modeling thematically describes a book, the topic mixture for documents was empirically evaluated. For example, the *Mitigation* chapter titled 'Technical Summary' from AR3 (Davidson, Metz, and others 2001) describes concepts outlined in Table 6. These concepts are taken directly from the table of contents in that chapter.

A subset of the mixture model for this document is shown in Table 7 for one assessment period. For simplicity only the four highest probable topics are shown. Topic composition clearly conveys a summarization of the Technical Summary.

Table 5: Citation & Parsing Retrieval Error Measures.

Book	*Precision*	*Recall*	*F-Measure*
Physical Science	0.91	.73	.81
Mitigation	.94	.58	.72
Impact	.91	.74	.82
Synthesis	.99	.81	.89

Table 6: Mitigation Technical Summary Table of Contents.

Concepts
Mitigate GHG
Greenhouse Gas Emissions
Buildings,Transport,Industry Sector
Agricultural,Waste Management,Energy Supply Sector
Hydrofluorocarbons and Perfluorocarbons
Potential of Greenhouse Gas Mitigation
Carbon Reservoirs and Geo-engineering
Mitigation through Terrestrial Ecosystem and Land Management
Social and Economic Considerations
Mitigation Options,Policies, Measures, and Instruments
International Policies and Measures
Adaptation and Mitigation Costs
Development, Equity and Sustainability Issues
Biological Carbon Mitigation
Economic Costs
Marine Ecosystem and Geo-engineering
Gross Costs of GHG Abatement
Costs of Domestic Policy to Mitigate
Carbon Emissions
Effects of Carbon Taxes
International Emission Trading
Benefits of Greenhouse Gas Mitigation
Spillover Effects
Results for Kyoto Targets
Change Mitigation Evaluated Nationally
Costs of Climate Change Mitigation
Coal, Oil, Gas, Electricity,Transport
Sectoral Ancillary Benefits of Greenhouse Gas Mitigation

Document Thresholding and Citations

Recall, each report chapter $ch_{n,m,l}$ has a set of citations $ci_{n,m,l,k}$ referenced at the end of the chapter. Given a cross-domain modeling experiment is performed, where the *Physical Science* citations is used as domain 1 $d1$ and *Physical Science* reports is used as domain 2 $d2$, it should be feasible to find all of the citations referenced in a particular report chapter by means of the model. After $d1$ and $d2$ are modeled and cross-domain pairs are obtained, a set documents from the two domains are clustered based on a threshold.

Table 7: Mitigation Topic Partial Mixture for Assessment Period 3.

22%	*14%*	*12%*	*10%*
climate change	climate change	climate change	climate change
energy efficiency	temperature	energy efficiency	renewable energy
emissions trading	ppm	renewable energy	greenhouse gas
policy	land use	adaptation	fossil fuel
cap and trade	carbon dioxide	technology transfer	wind
adaptation	scenario	policy	carbon dioxide
renewable energy	radiative forcing	forestry	carbon capture and storage
national	fossil fuel	building	power
greenhouse gas	adaptation	country	system
deforestation	carbon intensity	sector	policy

Table 8: How many citations can be recovered from the cross-domain model as the threshold is decreased.

Threshold	*Accuracy*
75	4%
50	15%
25	26%
10	43%
5	65%

This threshold is based on a ranked list of topic probabilities assigned to each document. The result of setting the threshold to a higher value means only the documents which have a high probability assigned for a topic will be retrieved. As the threshold decreases the number of documents retrieved will eventually reach the total number of documents in that model. These results are shown in Table 8.

In the experiments described in this paper, a higher threshold was used for citations (95%) and for reports a threshold of 75% was used. More experimentation is needed to determine optimal values for this thresholding.

The Physical Science and Impact Cross-Domain Model

This experiment used (40,60,70) topics K for the *Physical Science* citation model and (10,20,30) topics K for the *Impact* report model. There were multiple topic pairs found in this experiment, however one such example is shown. In this example, Figure 4 shows the topics in common among the *Physical Science* citations model and the *Impact* report model. Common themes from these topics are *sea level*, *land use*, *adaptation*, *temperature*, *impact* and *climate change*. The documents obtained from the two domains based on the low-divergence topic pairs, are shown in Table 9. As can be seen in Table 9, the citation found in domain *1* and the chapters found in domain *2* appear to relate to *coastal* and *oceanic issues*.

	Physical Science Citations Topic 15	**Impact Report Topic 2**
AR1	climate change, adaptation, risk, temperature, land use, sea level rise, impact, biodiversity, resource, vulnerability	climate change, temperature, sea level rise, ozone, global warming, weather, winter, impact, human, health
AR2	climate change, adaptation, temperature, risk, land use, impact, sea level rise, biodiversity, resource, vulnerability	climate change, temperature, weather, health, winter, impact, global warming, population, sea level rise, human
AR3	climate change, adaptation, temperature, risk, impact, resource, biodiversity, sea level rise, land use, vulnerability	climate change, temperature, adaptation, impact, sea level rise, weather, land use, summer, increased, winter
AR4	climate change, adaptation, temperature, biodiversity, impact, resource, risk, sea level rise, land use, vulnerability	climate change, adaptation, temperature, sea level rise, impact, weather, global average temperature, confidence, forestry, risk
AR5	climate change, adaptation, biodiversity, temperature, impact, resource, risk, sea level rise, land use, flood	climate change, adaptation, temperature, risk, confidence, biodiversity, urban, medium, weather, land use

Figure 4: Cross Domain Topic Similarity Model Results: Physical Science Citations Domain and Impact Report Domain.

The Physical Science and Mitigation Cross-Domain Model

This experiment used 80 topics K for the *Physical Science* citation model and 20 topics K for the *Mitigation* report model. Other values for K were used but yielded results with

Table 9: Cross Domain Document Cluster Results: Physical Science Citations Domain and Impact Report Domain.

Domain 1 Physical Science Citations		
AR		*Title*
3		Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. (Stirling et al. 1998)
4		Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. (Stirling et al. 1998)
Domain 2 Impact Reports		
AR	*Chapter*	*Title*
1	6	World oceans and coastal zones
2	9	Coastal Zones and Small Islands
3	6	Coastal Zones and Marine Ecosystems
3	17	Small Island States
4	6	Coastal systems and low-lying areas
4	16	Small islands
5	5	Coastal Systems and Low-Lying Areas
5	29	Small islands

divergences that did not meet the set divergence threshold. In Figure 5, the topic pair which yielded a low divergence is shown where the main themes relate to *forestry*, *sequestration*, *greenhouse gas*, *climate change*, and *co2*. The set of documents obtained from the two domains based on the low-divergence topic pairs, is shown Table 10. As can be seen in Table 10, the citation found in domain *1* is related to the chapters found in domain *2*.

	Physical Science Citations Topic 10	**Mitigation Report Topic 23**
AR1	forestry, deforestation, greenhouse gas, methane, climate change, forest, emission, anthropogenic, global warming, greenhouse effect	sequestration, carbon sequestration, forest, forestry, greenhouse gas, climate change, carbon sink, stock, kyoto protocol, carbon dioxide
AR2	carbon sequestration, sequestration, climate change, forestry, tonne, bottom, forest, cost, greenhouse gas, deforestation	sequestration, carbon sequestration, forest, forestry, greenhouse gas, climate change, carbon sink, stock, kyoto protocol, carbon dioxide
AR3	sequestration, carbon sequestration, forestry, land use, climate change, deforestation, forest, carbon cycle, atmospheric co2, kyoto protocol	sequestration, carbon sequestration, forest, forestry, greenhouse gas, climate change, carbon sink, stock, management, kyoto protocol
AR4	carbon sequestration, climate change, forestry, deforestation, sequestration, adaptation, land use, greenhouse gas, biodiversity, forest	sequestration, carbon sequestration, forest, forestry, greenhouse gas, climate change, carbon sink, stock, management, soil
AR5	land use, climate change, forestry, deforestation, biodiversity, greenhouse gas, sequestration, carbon sequestration, adaptation, redd	sequestration, carbon sequestration, forest, greenhouse gas, forestry, climate change, carbon sink, management, soil, stock

Figure 5: Cross Domain Topic Similarity Model Results: Physical Science Citations Domain and Mitigation Report Domain.

Table 10: Cross Domain Document Cluster Results: Physical Science Citations Domain and Mitigation Report Domain.

Domain 1 Physical Science Citations		
AR		*Title*
5		Can trees buy time? An assessment of the role of vegetation sinks as part of the global carbon cycle.
Domain 2 Mitigation Reports		
AR	*Chapter*	*Key Themes*
1	4	Forests, Carbon, Emission, Land
3	4	Land Use, Carbon, Forests
4	9	Forestry, Biofuels, Fossil fuels, Greenhouse gas
4	8	Emissions, Bioenergy feed stocks, Agriculture, Vulnerability
5	11	Agriculture, Forestry, Land Use

Impact Citations and Mitigation Report Cross-Domain Model

This experiment used 70 topics K for the *Impact* citation model and 10 topics K for the *Mitigation* report model. Other values for K were used but yielded similar results or no results. In particular, there was a single topic pair that was

	Impact Citations Topic 40	Mitigation Report Topic 12
AR1	climate change, adaptation, impact, intergovernmental panel on climate change, response, effect, land use, risk, greenhouse gas, research	climate change, principle, decision, greenhouse gas, adaptation, carbon sequestration, cost, energy efficiency, making, sequestration
AR2	climate change, adaptation, impact, intergovernmental panel on climate change, response, land use, risk, effect, greenhouse gas, research	climate change, carbon sequestration, decision, adaptation, principle, sequestration, greenhouse gas, dimension, cost, making
AR3	climate change, adaptation, impact, intergovernmental panel on climate change, response, risk, land use, greenhouse gas, effect, research	climate change, carbon sequestration, sequestration, energy efficiency, greenhouse gas, adaptation, land use, policy, cost, scenario
AR4	climate change, adaptation, impact, intergovernmental panel on climate change, risk, response, land use, greenhouse gas, research, vulnerability	climate change, land use, carbon dioxide, energy efficiency, sequestration, carbon sequestration, policy, scenario, greenhouse gas, carbon capture and storage
AR5	climate change, adaptation, impact, intergovernmental panel on climate change, risk, response, land use, greenhouse gas, research, vulnerability	climate change, land use, urban, greenhouse gas, city, infrastructure, policy, planning, carbon dioxide, transport,

Figure 6: Cross Domain Topic Similarity Model Results: Impact Citations Domain and Mitigation Report Domain.

discovered based on the divergence threshold of .1. The topics in common from the two domains are shown in Figure 6 with common themes around *climate change*, *adaptation*, *greenhouse gas*, *land use*.

The documents obtained from the two domains based on the low-divergence topic pairs are shown in Table 11. As can be seen in Table 11, the citations found in domain *1* are harder, empirically, to relate to the chapter found in domain *2* than the previous experiments. However, there is certainly relevance between the two sets of documents. For example, in the report chapter 12 from AR5 there is a theme around *settlement* which includes *urbanization*, *agriculture*, *emissions* etc. In the citations, there is a mix of themes ranging from *agriculture*, *greenhouse effects*, *drought*, *settlement*, *cities*, etc.

There were additional interesting results found among other experiments. For example, citations referenced in the *Mitigation* report were also found among *Impact* citations. Of the *Impact* citations that were modeled, these citations that were found to also exist among the *Mitigation* referenced citations correlated with the appropriate *Mitigation* report chapters.

Future Work

Future work will explore expanding the range of divergence threshold to increase the number of topic pairs, leading to potentially more document clusters. This is likely to yield more interesting cross-domain results.

Evaluating this work is a challenge due to the lack of availability of ground truth data. However, there are two approaches that could be used to evaluate this work. One such approach is to use human assessments to evaluate the document clusters and a second approach is to use citation analytics. Work is currently underway to quantitatively measure the goodness of the topics and the quality of the document clusters.

Conclusion

This work describes a method that uses micro-filtering and cross-domain modeling to understand how one domain influences another. In particular, the results in this paper convey a promising way of understanding how climate change citations may influence the various parts of the IPCC reports.

By understanding domain influence for a given scientific domain and how these influences change over time, specific concepts can be identified and their evolution can be modeled in relation to the influence of concepts from another domain. These influences could potentially be used to understand how a scientific field may continue to change over time, by analyzing which concepts probabilistically have downward trends, which concepts probabilistically have upward trends and what is the likelihood that these trends will persist.

Table 11: Cross Domain Document Cluster Results: Impact Citations Domain and Impact Report Domain.

Domain 1 Impact Citations

AR	*Title*
2	Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas MINK region. (Easterling III et al. 1993)
2	Pestriskanalysis and the greenhouse effect. (Sutherst 1991)
2	The flickering switch of late Pleistocene climate change.(Grootes, White, and Barlow 2002)
3	Effect of precipitation and temperature changes on the flow regime of the Danube river. (Starosolszky and Gauzer 1998)
3	Towards an integrated impact assessment of climate change the MINK study. (Rosenberg 1993)
4	Climate change: a looming challenge for fisheries management in southern Africa.(Clark 2006)
4	The impacts of climate change in coastal marine systems. (Harley et al. 2006)
4	Human Choice and Climate Change: An international assessment (Rayner and Malone 1998)
4	Climate change: overview and implications for wildlife. (Root and Schneider 2002)
4	Wildlife Responses to Climate Change: North American Case Studies. (Schneider 2002)
4	African droughts and dust transport to the Caribbean: climate change implications. (Prospero and Lamb 2003)
4	Implications for Irelands Marine Environment and Resources. (Boelens, Minchin, and O'Sullivan 2005)
5	Vulnerability of aquaculture in the tropical Pacific to climate change.(Pickering et al. 2011)
5	The use of religious metaphors by UK newspapers to describe and denigrate climate change. (Woods, Fernández, and Coen 2012)
5	Incorporating climate change into water resources planning in England and Wales. (Arnell 2011)
5	Increasing land pressure in East Africa: the changing role of cassava and consequences for sustainability of farming systems. (Fermont, Van Asten, and Giller 2008)
5	An integrated city-level planning process to address the impacts of climate change in Kenya: the case of Mombasa. (Kithiia and Dowling 2010)
5	Solastalgia: the distress caused by environmental change. (Albrecht et al. 2007)
5	Assessing the effects of climate change on the hydrological regime of the Limay River basin. (Seoane and López 2007)
5	Effects of Climate Change for Aquatic Invasive Species and Implications for Management and Research. (Thomas et al. 2008)
5	Is a transition to semipermanent drought conditions imminent in the U.S. Great Plains? (Hoerling et al. 2012)
5	Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond. (Warner and Schofield 2012)
5	The climate change matrix facing Maori society.(King, Penny, and Severne 2010)
5	What can we learn from long-term groundwater data to improve climate change impact studies? (Stoll et al. 2011)
5	When we dont know the costs or the benefits: adaptive strategies for abating climate change. (Lempert, Schlesinger, and Bankes 1996)
5	Dramatic declines in mussel bed community diversity: response to climate change? (Smith, Fong, and Ambrose 2006)
5	Climate change in sub-Saharan Africa: what consequences for pastoralism? (Ericksen et al. 2013)
5	Seaweed assemblage changes in the eastern Cantabrian Sea and their potential relationship to climate change. (Díez et al. 2012)
5	A conceptual framework for analyzing adaptive capacity and multi-level learning processes in resource governance. (Pahl-Wostl 2009)
5	Seed dispersal in changing landscapes.(McConkey et al. 2012)
5	Cities and Climate Change: Global Report on Human Settlements.(Habitat 2011)

Domain 2 Mitigation Reports

AR	*Chapter*	*Title*
5	12	Human Settlement Infrastructure Spatial Planning GHG cities urban areas energy GHG economies GDP land driver subregions air quality heat island

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